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PROGRESS REPORT ON FAST BREEDER REACTOR SAFETY STUDIES

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RADIATION DIVISION

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PROGRESS REPORT

ON

FAST BREEDER REACTOR SAFETY STUDIES*

by

L. A. Beach, A. G. Pieper, and M. P. Young

JUNE, 1958

*NRL Prob. No. 74H04-19.

ABSTRACT

A proposal was made to ANL for NRL to construct a gamma ray pin-hole camera to follow the flow of molten fuel elements by observing the emitted gamma rays with a TV chain viewing an image of the fuel elements on a NaI screen. However, an alternative system has been proposed that will give the same space resolution, improved time resolution and dynamic range with greater flexibility and reduced cost. This system consists of a rotating cylinder with a large number of small collimating holes scanning across the test section. Signals from scintillation detectors placed behind the drum will intensity modulate the Z axis of multi-gun oscilloscopes. A continuously moving film camera will record these sweeps for study and analysis.

STATEMENT OF THE PROBLEM

The Argonne National Laboratory is currently working on a program (designated as TREAT) to determine the safety of fast breeder reactors. A thermal reactor will be designed capable of melting natural uranium fuel rods placed in a test chamber at the center of its core. It is proposed to melt fuel pins of the type appropriate for fast breeder reactors (except for enrichment) and determine as much as possible about the subsequent behavior of the molten fuel. Initial studies would be made with dry fuel pins and later studies would involve fuel pins immersed in sodium. The most difficult problem in the latter measurements is to follow the motion of the molten fuel surrounded initially by the sodium coolant, a situation that precludes any visual measurement procedure. Consideration of this problem by representatives of Argonne and Los Alamos failed to suggest any approach for following the molten metal other than the use of the nuclear radiation emanating from the fuel itself. This radiation can, in principle, be made to display the motion of the fuel by using a pin-hole camera technique[1]. This method is limited by the intensity of the radiation and the inherent characteristics of the pin-hole camera.

It would be desirable to follow the motion of individual fuel pins of diameter approximately 0.15 in. which are normally spaced closely together. The desired time resolution is set by the motion of the molten fuel pins, and cannot be accurately predicted in advance. From discussions among ANL and NRL representatives on 30 April 1957, it was felt desirable to have a spatial resolution at the fuel pins of 1/10 in. or less, and time resolution perhaps as small as one millisecond if this were possible.

While the initial measurements will probably involve a few pins, perhaps a row of pins across the width of the test chamber, it is desired ultimately to view a complete cluster of fuel pins. However, any experimental approach observing the

[1] A preliminary discussion of this technique is contained in a letter from Bob Watt, LASL, to David Okrent, dated Apr. 2, 1957.

gamma rays leaving the outside face of the test chamber cannot view fuel elements within a cluster because of the attenuation of outside pins. Thus it cannot be expected to record melting of any pin in the cluster in line with any other pin that does not melt.

TREAT REACTOR CHARACTERISTICS

The Argonne proposal is to construct a thermal neutron reactor with maximum core dimensions of 6 x 6 x 4 ft. high with a test chamber located at its center and arrangements made for viewing this chamber through ports. The fuel pins to be used are to be approximately 16 in. long and the test chamber is to have dimensions of 4 x 4 x 16 in. Consequently, the area which it is desired to observe is 4 in. wide by 16 in. high. A 2 ft. graphite reflector surrounds the core. The shield of the reactor will be 5 ft. of magnetite concrete.

The melting of fuel pins would be effected by a reactor transient with the power rise following a period of as short as 5 milliseconds. Slower transients are anticipated depending upon the needs of the program.

GENERAL DESCRIPTION OF THE ORIGINAL PROPOSED PIN-HOLE CAMERA SYSTEM

The proposed system consisted of a gamma ray pin-hole approximately 2 meters from the test chamber and a 1 in. thick sodium iodide screen approximately 2 meters from the pin-hole. Thus, an image of the test chamber would be formed on the sodium iodide screen with approximately unit magnification. The gamma rays falling on the screen cause it to fluoresce and this light is focused on the cathode of an image orthicon television pick-up tube. A low noise television chain and appropriate recording equipment record a reproduction of the optical image formed on the sodium iodide screen. This image is photographed to permit subsequent detailed study and analysis.

The installation requires careful and rather massive shielding. A slow neutron curtain is required at least on the reactor side of the equipment. The element of the system requiring the greatest shielding is the sodium iodide screen; however, the image orthicon must not be subjected to intense radiation.

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ESTIMATES OF SIGNAL STRENGTH

Calculations of predicted signal strength were made assuming the nuclear pin-hole would have a diameter of 0.05 in. and that a 1 in. sodium iodide screen would be employed with distances from test chamber to pin-hole and pin-hole to screen each 2 meters. The use of a fast lens (F.75), an image orthicon pick-up tube (6849) and a Bendix-Friez television chain was assumed. The light level necessary to obtain a useful record was determined largely by comparison with a somewhat similar arrangement then in use at NRL rather than by straight computations based upon quoted tube characteristics.

The radiation from the fuel pins was computed for two situations, the first applying to the period during which the pins were being melted when the prompt fission gammas are the most important source and the second to subsequent times when it was assumed that only the delayed gamma rays from the fissions necessary to melt the fuel pins would be available. In the first case, a reactor power transient was assumed in which the power rose with a 5 millisecond period and was shut down by the insertion of 10% negative reactivity. From these results other situations of interest can be assessed without too much difficulty.

Prompt gamma rays emanating from the fuel pins during the transient are primarily prompt fission gammas and the results are summarized in Table 1. Capture and inelastic scattering gammas in the uranium, sodium bond and stainless steel clad were calculated but are smaller than the prompt fission gammas. It is estimated that due to the amount of excess negative reactivity that can be inserted, this prompt gamma intensity will not decrease more than a factor of 10 before leveling off into an 80 second period caused by delayed neutrons. Therefore, these prompt fission gamma will be bright enough to follow the motion of the molten fuel for some time. The brightness of capture gamma rays in the sodium coolant will be much less than the fuel pin brightness.

Delayed gammas from fission products, which for short times can be considered as equal to the number of fissions decaying with a lifetime of one second, were also estimated. These decay gammas are a factor of 100 below the peak prompt gammas for a 5 millisecond transient; consequently, they will not become important until very late times. Contrast between fuel pins and sodium coolant is good but gammas from the reactor behind the test section must be attenuated.

As will be discussed later, the present NRL arrangement indicated that a gamma brightness of approximately the level furnished by the decay gamma rays was necessary to get the desired spatial resolution even with a time resolution of 1/30 second. If transients of longer periods are observed, the prompt gammas will not be as much greater than the delayed gammas. In fact for a transient with 0.5 second period, it is estimated that the peak of the prompt gamma rays will be approximately equal to the delayed gammas.

SPATIAL RESOLUTION

The spatial resolution possible in the measurement is limited principally by three considerations: (1) the pin-hole characteristics, (2) geometrical optics at the sodium iodide screen, and (3) the characteristics of the image orthicon tube.

The pin-hole design is dictated principally by two considerations, namely, the size of the pin-hole (assumed 0.05 in.) and the field of view to be imaged by the pin-hole. The desired field of view, assumed 4 x 16 in. at the test chamber, and the test chamber to pin-hole distance (assumed 2 meters) determine the configuration of the pin-hole. In order to avoid limiting the field of view, the pin-hole must be made of two rectangular pyramid-shaped voids with the sides of their bases in the ratio of 4 to 16 and their vertices placed together. Table 2 shows computed values of the intensity of gamma rays from a point source reaching the screen. The width at half intensity across the short dimension of the field of view is much more narrow than the traverse at right angles. Thus, the image formed by such a pin-hole must of necessity be astigmatic. The pin-hole design is quite critical and it was proposed to make an insert of a high density metal.

The resolution is further degraded for points away from the axis of the system by the geometrical optics in the sodium iodide. The light going to the image orthicon makes an angle with the direction of the gamma ray creating the light, thus with a 1 in. thick sodium iodide screen and a mirror on the side toward the pin-hole, this effect will produce a maximum smearing of .05 of an inch for points 2 in. off the axis and .2 of an inch for points 8 in. off axis. This effect is most troublesome when viewing points at the top and bottom of the test chamber.

The image orthicon tube has the characteristics of showing poor resolution at low incident light levels. Thus, if the intensity is too low the resolution becomes poor.

Insight into possible resolution using a television chain looking at a NaI screen was obtained by taking pictures of the display from the NRL arrangement. Radiographic pictures were taken using a gamma ray intensity at the screen of approximately 10^7 Mev of γ's/cm^2-sec. Single objects 1/8 in. in diameter, either lead rods 3/4 in. long or holes in a 3/4 in. lead plate, are recorded in a single frame (1/30 sec.). When pairs of 1/8 in. holes in a 3/4 in. plate are viewed, they are shown resolved when the center-to-center distance is 5/16. The NRL arrangement has a field of view of 24 in. compared to an anticipated 16 in. for these experiments; consequently, one would expect resolved distances to decrease in ratio 16 to 24 to approximately 0.1 diameter and 1/4 in. center-to-center separation with this time resolution.

It appears that a spatial resolution of approximately .1 in. in the horizontal plane and somewhat worse in the vertical plane is the best that can be obtained because of the penetration of gamma rays through the edge of the pin-hole, an effect that is independent of intensity. As proposed, other effects will not worsen the matter seriously except when the intensity becomes low enough for the image orthicon picture to become poor.

TIME RESOLUTION

The time resolution that can be obtained is expected to be limited by the intensity that can be obtained. That is certainly the case with the image orthicons presently available. Should the intensifier image orthicon currently being worked on by RCA become available, the limitation might become one of scanning and recording mechanisms. For this application it is possible, without very much development work, to scan an image orthicon at rates up to 180 per second and build the necessary recording equipment. This proposal assumed the construction of equipment capable of several scanning rates ranging from 30 to 180 scans per second.

DYNAMIC RANGE

The dynamic range of an image orthicon is rather restricted and is roughly a factor of 20 to 1. (Probably less than this if the image orthicon is set for maximum resolution). Consequently, it would not be possible for a single image orthicon to follow both the high intensity signal due to a rapid heating of the fuel pins and the subsequent low intensity following the transient unless it is possible to control the light incident on the image orthicon. Further, unless the light from the peak of the excursion is stopped from reaching the image orthicon, it would not record subsequent low level signals. Consequently, it was proposed to arrange a shutter which will open quickly when the light level has fallen to a value which the image orthicon can record.

EXPECTED PERFORMANCE

From the analysis conducted it appears that equipment with a nominal .1 - .15 in. resolution on axis can record the gamma rays from the molten fuel material with a scan rate of 30 per second. This means one would obtain a picture integrated over approximately 1/30 of a second every 1/30 of a second. Should the RCA intensifier image orthicon become available and live up to its advanced billing, it is reasonable to expect that 180 scans per second could be obtained by its use.

RADIATION SCANNING SYSTEM

Although the above proposed pinhole camera with TV chain system could obtain a reasonable spatial resolution, the time resolution obtainable is only 30 frames per second. An increase in the number of frames per second to 180 is dependent upon the availability of the new RCA intensifier image orthicon tubes, production models of which are still unproven. The dynamic range of the proposed system was also severely limited, particularly when the TV chain was adjusted for maximum resolution. To obtain completely the desired information from each NaI screen requires two TV channels. The cost of equipment purchases and the construction of the pin-hole and associated heavy shielding for a single TV channel would amount to approximately $125,000. An additional $50,000 is required for a second TV chain to view the NaI screen to increase the dynamic range to cover the entire transient.

By the time the contract for NRL to participate in the TREAT program was completed early in 1958, an alternative system had been partially evolved that will give the approximate space resolution of the above system and 250 frames per second with a dynamic range of approximately 50. The analogy of the flying spot scanner of early television started discussions that led to the new system. This system involves a rotating drum with a large number of collimating holes scanning the test section. Gamma rays from the fuel pin will penetrate through these collimating holes onto a multi-section NaI crystal.

Signals from photomultipliers viewing these NaI crystals will, after amplification, intensity modulate the Z-axis of two multi-gun oscilloscopes. Sweeps of these oscilloscopes will be recorded on a continuously moving film camera for later study and detailed analyses. This system was discussed in qualitative terms with representatives of ANL on March 4, 1958.

A slit arrangement narrowing down to .4" proceeding the rotating drum will limit the amount of radiation illuminating the drum. Additional shielding will also be provided behind the drum to protect the NaI crystals from background radiation from other parts of the reactor. The entire mechanical arrangement of the slit, drum and shielding will be mounted and aligned on a single sliding arrangement that can be easily inserted into the reactor.

The rotating drum will be 22" in diameter and 18" in height, with a hollow center of 7" in diameter. Eighty series of holes .2 of an inch apart will scan the 4" x 16" test section as the drum is rotated at approximately 1000 r.p.m. These holes will be 15 mills in diameter with collimation or definition of the hole provided by a steel rod 1/16 of an inch in diameter with a 15 mill hole through it. The drum will be filled with a high density metal to attenuate all other uncollimated radiation below the desired signal. The drum will be rotated by a hydraulically driven motor on a vertical axis nine feet from the test section in the viewing hole of the TREAT shield. The hydraulically driven motor will allow rotations at all speeds slower than 1000 r.p.m.

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The spacing of the holes may be described as follows: Eight holes will be placed 2 inches apart in a vertical line. At a rotation of 2.1 degrees and displaced downward by .2 inches will be another series of 8 holes, etc., for a total of ten such vertical series. This group of ten vertical series of holes will be repeated a total of eight times around the drum for a total of 640 holes. There will be an additional spacing of 1.35 degrees of rotation between the eight groups to provide blanking between frames on the film. Only one vertical series of holes will be visible at the test section at a time through the slit jaws. Since gamma rays will go through each hole twice per revolution, there will be 16 frames per revolution.

The fabrication of a suitable drum is the biggest difficulty of this system. To provide desired spatial resolution with a useable signal intensity requires a proper balance between small collimating holes and a large drum diameter. Since the intensity levels limit the minimum hole diameter to 15 mills, this requires a drum diameter of 22" to give a desirable space resolution. This is approximately the largest diameter drum that will fit in the current shield design. Obtaining straight holes .015" in diameter through a material that will provide an attenuation to gamma radiation of $10^8 - 10^9$ is difficult but appears solvable.

The gamma rays penetrating each group of ten horizontal series of eight holes will strike a separate NaI crystal, 0.5" wide, 2" high and 2" deep. Therefore there will be eight crystals with appropriate photomultipliers tube and power supplies converting the light pulses into electrical signals.

The recording system will be built around two four gun oscilloscopes. The signals from the eight photomultiplier tubes viewing the NaI crystals will, after amplification, intensity modulate the Z-axis of these oscilloscopes. The four sweeps of each oscilloscope will be triggered simultaneously by a signal from a magnetic pick up from the rotating drum. The time duration of each sweep will be 400 microseconds and the sweep length on the oscilloscope face will be 2-1/2 cm. The four sweeps of each oscilloscope will be placed end to end on a single horizontal line across the oscilloscope face. A camera will record these sweeps on 35 mm film moving at 1800 inches per minute. Each of the two films will have in four vertical rows, successively, frames of 2" sections of the test section. Cameras are available that can move film at all speeds from 0 up to 12,000 in/min.

SPATIAL RESOLUTION

The spatial resolution obtainable by this system primarily is determined by the diameter and length of the collimating holes. However, the limit in spatial resolution is determined by the intensity of gamma radiation reaching the crystal through the collimating hole. It appears that a reasonable spatial resolution with a useable signal is obtainable with a 15 mill collimating hole 22" long. This will provide a spatial resolution of .15 inches when the center of the drum is placed nine feet from the test section. This spatial resolution is slightly larger than the geometric optical resolution because gamma rays penetrate the lip of the collimating holes. This spatial resolution will be obtained in both the horizontal and vertical directions but the spacing between scans in the vertical direction is 0.2". This spatial resolution will be constant over the entire test section. Each scan across the test section will be 400 microseconds in time duration which will mean that the diameter of a test fuel pin will be swept across in 15 microseconds.

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CHECKS ON SPATIAL RESOLUTION

Experimental measurements have been made to determine actual resolution obtainable with small holes through a lead block. Gamma rays from a 1300 curie Co^{60} source were allowed to illuminate, through a slit arrangement, a 14" thick lead block. Radiation penetrating a .033" hole was detected by a NaI crystal shielded against radiation from all other directions. The source consisted of ten pins 5" long by 1/2" in diameter which were equally spaced around a circle of 5" in diameter. The entire source arrangement was in a water-tight aluminum can. This source at a distance of 10 feet from the lead block was moved on a line perpendicular to the axis of the hole. The resulting signal from the detector for traversing

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a single pin is shown in Fig. 1. The measured width at half maximum is 0.67" which can be accounted for by the straight geometrical optics of the arrangement taking into account the diameter of the source pins and the reduction of the hole length by one mean free path to compensate for gamma rays penetrating the lip of the hole.

Similar runs were made with the distance from source to collimating hole reduced by a factor of two to demonstrate the change in width of the response curve with distance. Also observations were made with a hole diameter of .055". With a monoenergetic source such as used here, discrimination against small pulses can improve the ultimate space resolution by eliminating more scattered radiation than direct unscattered radiation. With the above arrangement it was possible to increase the peak to valley ratio by a factor of 2.

SIGNAL STRENGTH CALCULATION

Using the typical data from Table 1, an estimate of the signal strength can be computed. With a .015" hole diameter in a 22" diameter drum 9' from the test section, an area of approximately .15" in diameter (or .11 cm^2) will be viewed at the test section. Therefore, when the hole is viewing a fuel pin at the peak of the transient, the source strength of the viewed will be 4.5×10^{15} mev of γ's/sec. The solid angle of the hole is 1.2×10^{-9}, so that the rate of radiation striking the crystal is 5.5×10^{6} mev of γ's/sec. Since the time to sweep across a fuel pin is 15 μsec, the amount of radiation from the fuel pin to strike the detector is 85 mev of γ's.

The above calculations are for a transient with a 5 millisecond period but the latest information from ANL indicates that they will probably do most of the work with transients of 50 - 80 milliseconds. At a 50 millisecond period, the peak gamma ray levels would be a factor of ten lower than above. The time of interest, i.e., when the fuel is flowing after a melt-down, will be after the peak gamma ray level has been past but with this slower period, the prompt γ-ray level should not fall more than a factor of 5 in the time of interest. However, due to the flexibility of the system, by a reduction in drum rotation and camera speed, some loss in intensity levels for slower transients can be compensated for by fewer frames per sec.

DYNAMIC RANGE

The dynamic range of this system is limited by the ratio of the signal to background. The background is primarily determined by radiation from the test section coming through the slit and consequently penetrating the drum. The attenuation provided by the drum for this radiation must be at least a factor of 10^8. By proper adjustment of other shielding, all other sources of background radiation must be made negligible in comparison to this factor. Contrast of the fuel pins to background radiation from regions of the reactor behind the test section must be improved by the addition of 2-3" thickness of Pb or Bi behind the test section to attenuate gamma rays from the reactor.

COST

The cost of this system is estimated to be appreciably less than the pinhole camera and TV system. The mechanical construction of the drum and shield is estimated to be approximately $25,000. The cost of the recording system including the NaI crystal amplifiers, 2 oscilloscopes and 2 cameras, plus test equipment, is estimated at approximately $25,000. This total of $50,000 is in comparison with approximately $125,000 for the previous system. Neither set of figures include design, checking out or installation costs. Nor do they include salary cost of division personnel working on the project.

STATUS

At present the design and method of fabrication of the rotating drum is currently being worked out. Details of this and other parts of the system will be reported on in the next report covering the period up to 30 June. Construction of the mechanical system will be started by then and should be completed in time to allow testing of the entire assembled system here at NRL during the Fall. Since TREAT is estimated to go critical late in 1958 or early in 1959, the system would be ready for installation in TREAT before transient testing is begun in the early part of 1959.

Lead has been cast in a steel drum 14" in diameter and 2" high to study fabrication techniques and will be used for additional checks on resolution and intensity requirements. Several small holes .020" - .040" were made through this drum by stretching piano wires across the steel drum before the lead was cast. These wires are pulled out after the lead has cooled. Upon rotation these holes will scan across small Co^{60} sources. Signals from NaI detectors will be used to demonstrate intensity modulation of an oscilloscope and determine the intensity levels and associated amplification required.

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TABLE 1

RESULTS OF INTENSITY CALCULATION FOR A 5 MILLISECOND PERIOD

Heat to melt uranium	60 cal/gm
Number of fissions to melt uranium	10^{13} fiss/gm
Peak fission rate assumed*	10^{15} fiss/gm-sec
Peak gamma-ray source strength in fuel	10^{17} Mev of γ's/cm^3-sec
Peak gamma-ray source strength in sodium	6×10^{14} Mev of γ's/cm^3-sec
Peak gamma-ray source strength in graphite reactor	5×10^{15} Mev of γ's/cm^3-sec
Peak Brightness of fuel pin	4×10^{16} Mev of γ's/cm^2-sec or 3×10^{15} Mev of γ's/cm^2-sec-ster.
Brightness of sodium one cm thick	6×10^{14} Mev of γ's/cm^2-sec
Brightness of graphite reactor behind test section	10^{17} Mev of γ's/cm^2-sec
Peak brightness of NaI screen through .05 diameter pin-hole with screen four meters from test section	10^9 Mev of γ's/cm^2-sec
Brightness of fuel pin from decay gamma rays from fission products	3.7×10^{14} Mev of γ's/cm^2-sec
Screen brightness from decay gammas	10^7 Mev of γ's/cm^2-sec

*This peak fission rate is averaged over the last period and it assumes that the uranium melts at the peak or during the initial decrease of the transient.

TABLE 2

COMPUTED INTENSITY AT SCREEN FROM A POINT SOURCE OF GAMMA RAYS*

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Percent of Maximum Intensity	Width of Spot (inches)			
	Horizontal		Vertical	
	Lead	Mallory 1000	Lead	Mallory 1000
100%	0.1	0.1	0.1	0.1
50%	0.132	0.124	0.225	0.19
10%	0.20	0.17	0.51	0.39
5%	0.23	0.194	0.63	0.48

* Values are for the most penetrating gamma ray energy.

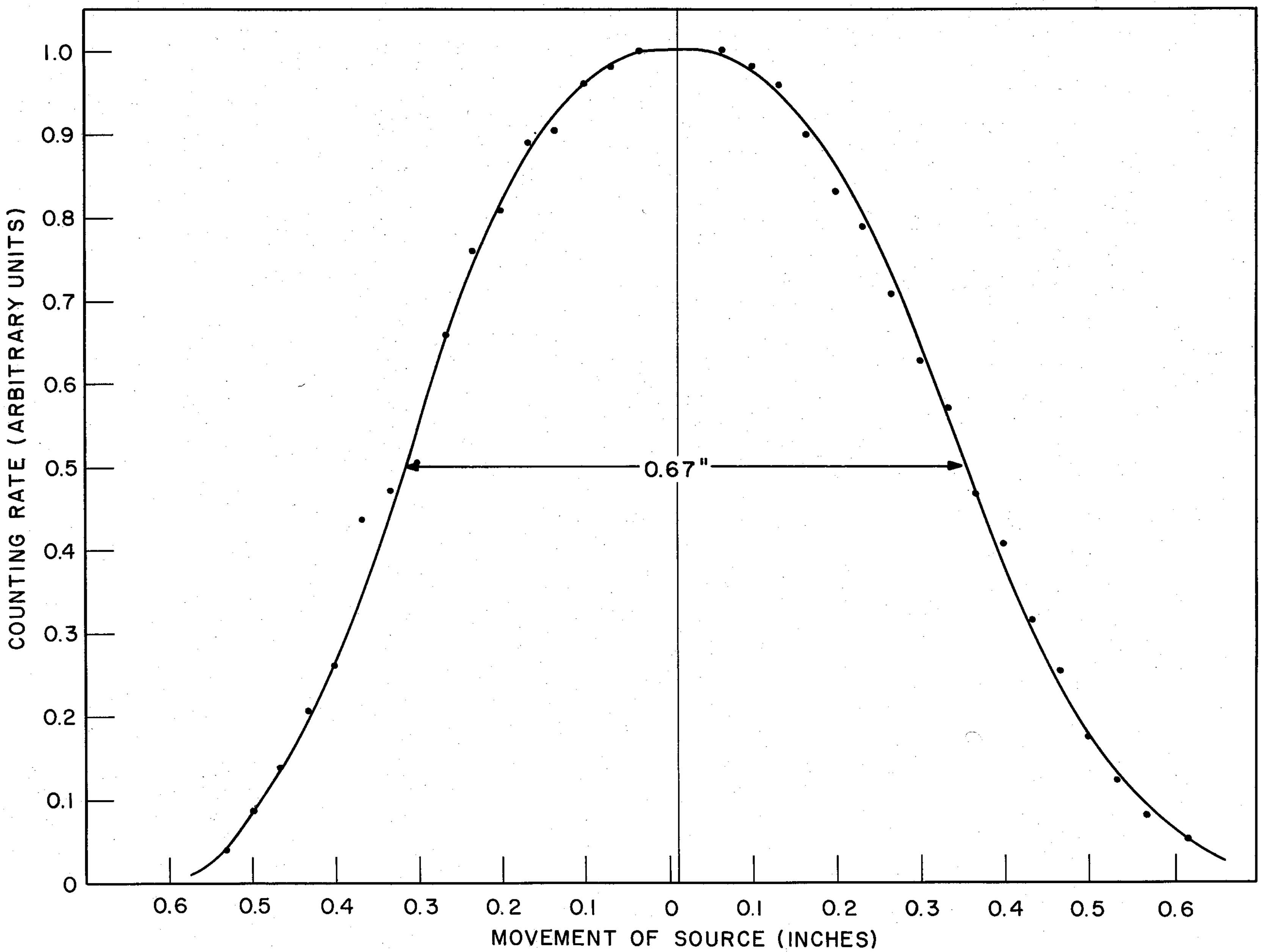
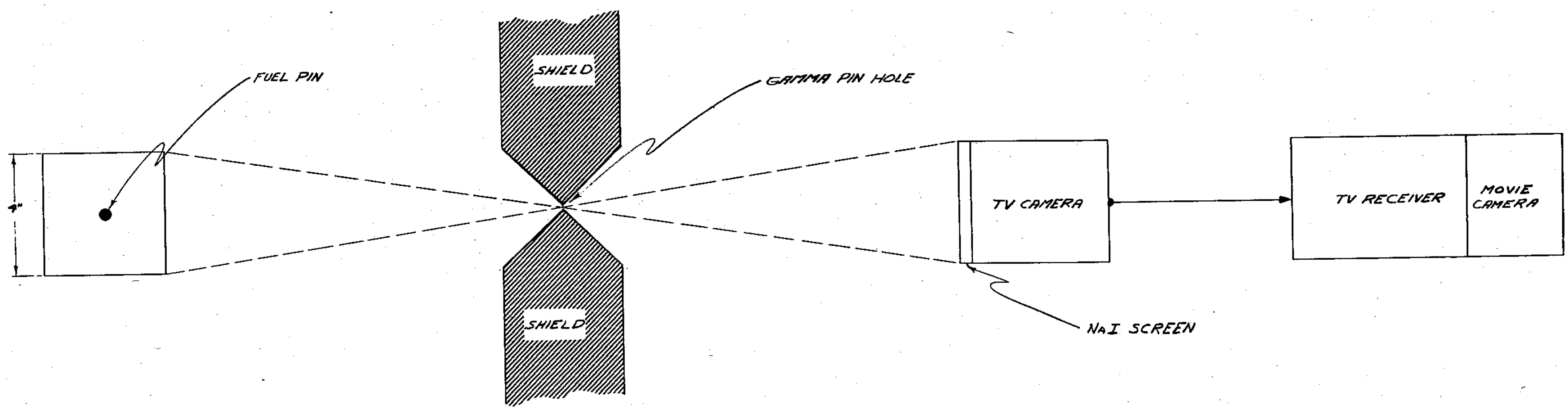


Figure 1 - Counting Rate as a pin of a 1300 curie Co^{60} source is moved perpendicular to the axis of a .033-in. collimating hole



Originally Proposed Gamma Ray Pin-Hole Camera System

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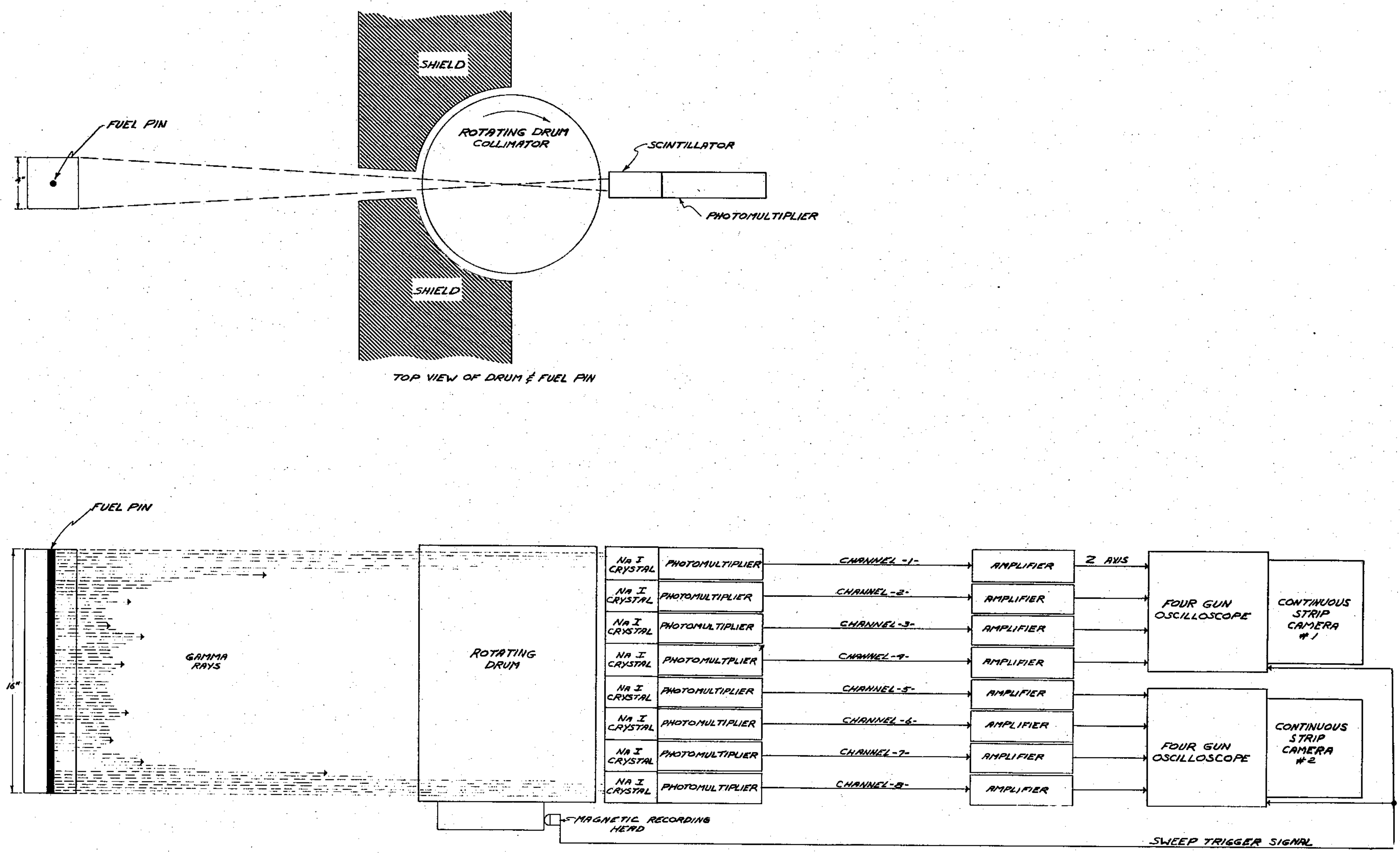

Presently Proposed Scanning Collimator System

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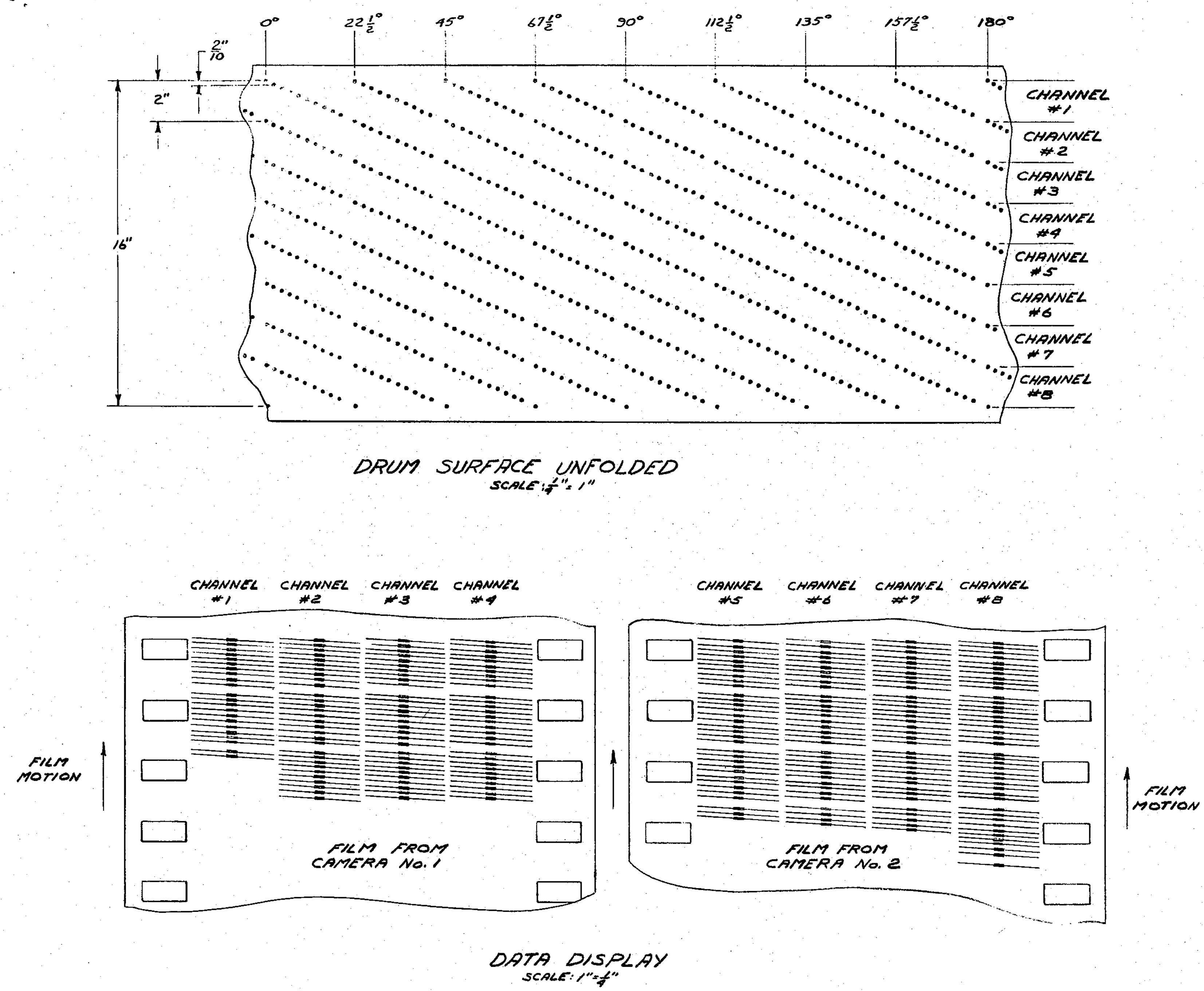

Presently Proposed Scanning Collimator System